PRODUCTION TRENDS OF SHALE GAS WELLS

A Thesis

by

WAQAR ALI KHAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee,	Robert A. Wattenbarger
Committee Members,	Walter B. Ayers
	Yuefeng Sun
Head of Department,	Steve Holditch

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ABSTRACT

Production Trends of Shale Gas Wells. (December 2008)

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Chair of Advisory Committee: Dr. Robert Wattenbarger

To obtain better well performance and improved production from shale gas reservoirs, it is important to understand the behavior of shale gas wells and to identify different flow regions in them over a period of time. It is also important to understand best fracture and stimulation practice to increase productivity of wells. These objectives require that accurate production analysis be performed. For accurate production analysis, it is important to analyze the production behavior of wells, and field production data should be interpreted in such a way that it will identify well parameters. This can be done by performing a detailed analysis on a number of wells over whole reservoirs.

This study is an approach that will lead to identifying different flow regions in shale gas wells that include linear and bilinear flow. Important field parameters can be calculated from those observations to help improve future performance. The detailed plots of several wells in this study show some good numbers for linear and bilinear flow, and some unique observations were made. The purpose of this work is to also manage the large amount of data in such a way that they can be used with ease for future studies. A program was developed to automate the analysis and generation of different plots. The program can also be used to perform the simple calculations to calculate different

parameters. The goal was to develop a friendly user interface that would facilitate reservoir analysis.

Examples were shown for each flow period, i.e. linear and bilinear flow. Different plots were generated (e.g; Bob Plot (square root of time plot) and Fourth Root of Time Plot, that will help in measuring slopes and thus reservoir parameters such as fracture permeability and drainage area. Different unique cases were also observed that show a different behavior of well in one type of plot from another.

DEDICATION

I dedicate this work to the Almighty God, for the blessings, strength and protection HE granted to me and for making my path easy for me whenever I faced problems. Also, I dedicate this work to my loving, caring and supportive family members and my all time encouraging friends who made my work complete and whose prayers and enlightenment always gave me moral support and encouragement.

ACKNOWLEDGEMENTS

I deeply wished to express my heartfelt gratefulness and gratitude to the following people who guided me and assisted me in every step of my work and supported me at every step during this work. I would like to thank Dr. Robert Wattenbarger, Professor of Petroleum Engineering, who served as the chair of my graduate committee. His guidance, serenity, commitment and support helped me to complete this work. I feel proud to be a student of a professor who always encouraged me and motivated me for my bright future. His friendly supervision made my work more interesting and full of dedication. I would also like to thank Dr. Walter B. Ayers and Dr. Yuefeng Sun, for their active contribution.

I would like to thank Tai Pham, EOG Resources, for providing me with the data and giving me a chance to understand things in a broader way.

I express my thanks to the Fulbright Association, which gave me the opportunity to come to the Harold Vance Department of Petroleum Engineering for my master's program under such a helpful and dedicated scholarship program.

I also thank all my professors for giving me the best of their knowledge and for empowering me with the best tools and techniques that led to this degree. I am grateful to my colleagues and friends who at every step supported me. My special appreciation goes to all my friends who helped me a lot in different ways and made my life and work even more enjoyable here in College Station.

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CHAPTER I

INTRODUCTION

1.1. Problem Description

Shale gas reservoirs are unconventional natural gas reservoirs that are having an increasing focus of activity in United States. In recent years, interest has increased in developing and producing shale gas reservoirs. **Fig. 1.1** shows shale gas plays in United States. Development of few shale gas reservoirs in late 90's demonstrated important success in shale gas production. Shale gas is considered to be self-sourcing gas reservoirs and these formations are extremely abundant worldwide. It is of major interest in U.S but even after having several commercial and exploratory shale gas plays its properties and production analysis is still under major study. Due to the complexity of shale reservoirs in terms of fractures and very low permeability (10-100 nano Darcy's) there is still a lot of work that needs to be done in order to understand different flow behaviors in these reservoirs. Production forecasts and more economic production techniques require understandings of shale gas reservoirs. Due to this complexity and variability of Shale gas reservoir properties with in fields and techniques that give good results in one area might be of less interest in others. It is important to clarify shale properties and fracture networks in order to use the best engineering practices for better economic recovery of gas resources from shale.

To make useful and productive future estimates it is important to understand

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This thesis follows the style of *Society of Petroleum Engineers Journal*.

different flow regions during production analysis of shale gas wells. By integrating knowledge for drainage volume, OGIP, rate forecast, reservoir characteristics and fracture network characteristics engineers can apply best technology practices to optimize production from future wells.

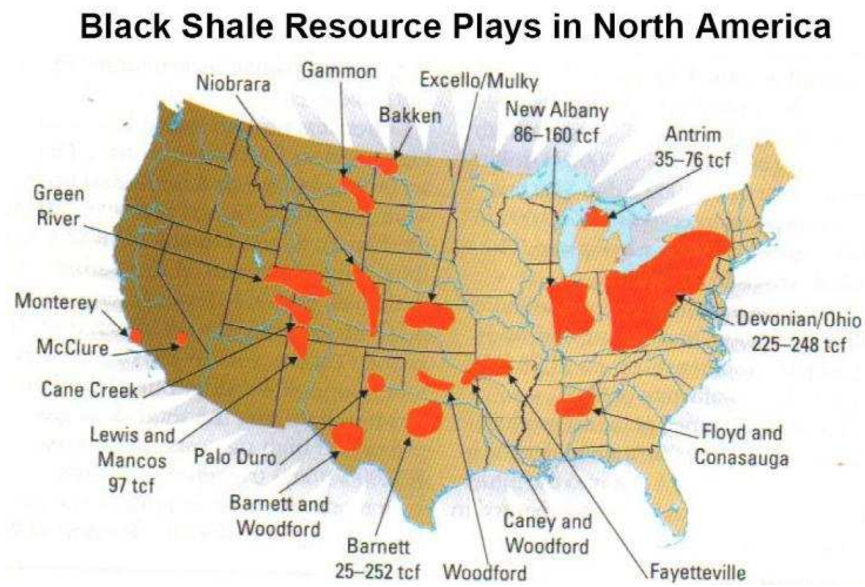


Fig. 1.1 Unconventional gas plays-major U.S. shale gas basins (Westside Energy Corporation [1])

1.2. Goals and Objectives of Research

The main goals of this research were to:

1. Analyze the production data from shale gas wells.
2. Manage data in order to keep it in systematic format to keep track of wells for future studies.
3. Make Production vs. Time plots (Log Log plot) to characterize the flow behavior and type of flow.

4. Make $\Delta m/q$ vs. $\sqrt{Time}$ plots (Bob Plots) to determine the slope and intercept.
5. Generate water gas ratio, Cartesian, Semi Log, and quarter plots to understand the behavior of Shale well.
6. Perform the analysis from the information available from the plots of linear flow in future work.
7. Observe the behavior of different wells over time and to clarify how different fracture methods affect the production.
8. Perform the analysis from the information available from the plots for bilinear flow.
9. Calculation of reservoir parameters like drainage area, fracture permeability, OGIP.
10. Develop an excel based computer program capable of doing all the above tasks automatically and ;
11. Group wells for future predictions.

1.3. Research Methodology

This research is an effort to manage provided well data efficiently and to analyze the data for different flow regimes and to understand well behavior under different conditions. This research will help in identifying the problem and identify any solutions that can be helpful for better well production.

The research is focused on identifying the linear and bilinear flow in different wells. Field data is used to do that and calculations made for linear flow to measure different reservoir parameters. Also bilinear flow is also analyzed which is a step forward for more detailed future work.

1.4. Thesis Outline

The study is divided into seven chapters. The outline and organization of this thesis are as follows:

Chapter I present an overview of the problem description, goals of research and research methodology.

Chapter II presents a comprehensive literature review to cover the basic concepts and to give an overview of the comparison of this study with the previous work.

Chapter III details the data management portion and gives an overview of the type of data.

Chapter IV gives details about the Computer program and its description and its capabilities. Chapter V discusses different graphical observations made from this study after plotting the data.

Chapter VI presents brief information about the data analysis and Chapter VII summarizes the conclusions from this work and recommendations for future research work.

CHAPTER II

LITERATURE REVIEW

2.1. Introduction

This chapter review previous work done and different techniques that are in use for effective well production e.g. hydraulic fracturing techniques and micro seismic monitoring to understand fracture networks.

2.2. Previous Work Done for Linear Flow Analysis

Different studies are performed spread over the years on low permeability reservoirs that include tight gas reservoirs and flow regions identified which tells us about the behavior of the reservoir over a period of time. Different Linear calculations made in order to measure different reservoir parameter by the help of history matching and flow behavior that helps in better future predictions. Following is an overview of these studies:

El-Banbi [2] and El-Banbi and Wattenbarger[3] presented an approach for the analysis of Linear Flow in gas well Production. The study presented new Laplace transform linear solutions for the analysis of pressure and production performance. During their study they presented that a more precise and practical approach is possible for well test analysis in case of linear flow. In their study it was shown that constant rate solutions are different than the constant pressure solution and wrong approach and use of equations results in erroneous estimates and results.

Arevalo-Villagran et al.[4] during their study back in 2001 on long term linear flow in tight gas wells presented a detailed approach. Their study is focused on decline curve analysis methods. They showed a simple analysis for calculating different reservoir parameters. The information in there analysis can be used to estimate K xe, drainage area, pore volume and OGIP. These calculations can be made by finding the slope of a Δm/q vs. √Time plot and detecting for the point where outer boundary effect occurs. **Fig. 2.1** shows an example of such a plot:

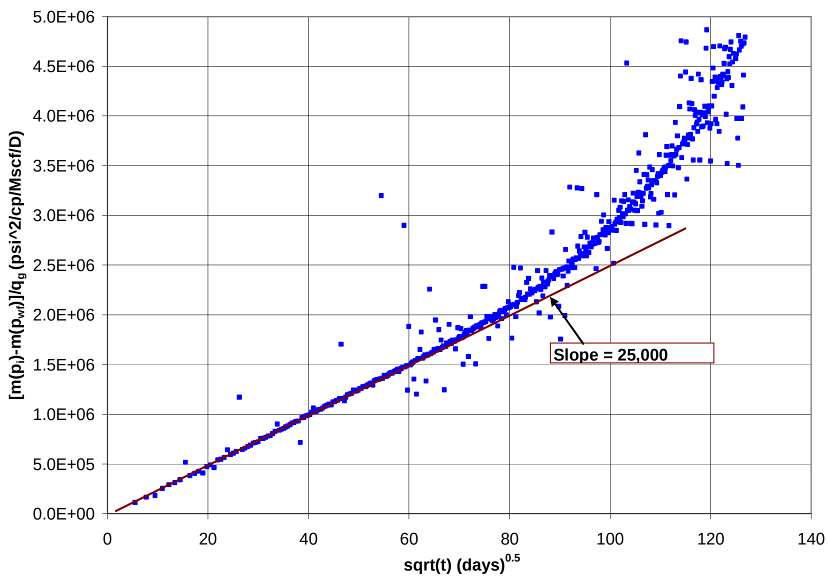


Fig. 2.1 Plot of $[m(p_i)-m(p_{wf})]/q_g$ *vs.*$\sqrt{Time}$,Showing slope before outer boundary is reached.(Ibrahim and Wattenbarger [5])

Table. 2.1 shows the formulae from their paper that can be used for analysis; different formulations are used for constant rate and constant pressure cases.

Table. 2.1 Interpretation formulas for linear flow regime for both constant q_g production and constant p_{wf} production (Arevalo –Villagran et al.[4])

Constant q_g production	Constant p_{wf} production
$\sqrt{k}A_c = \frac{803\,T}{\sqrt{(\phi\mu_g c_t)_i}}\left(\frac{1}{\tilde{m}_{CRL}}\right)$	$\sqrt{k}A_c = \frac{1262\,T}{\sqrt{(\phi\mu_g c_t)_i}}\left(\frac{1}{\tilde{m}_{CPL}}\right)$
$A = \frac{128\,T}{(\phi\mu_g c_t)_i}\left(\frac{\sqrt{t_{esr}}}{\tilde{m}_{CRL}h}\right)$	$A = \frac{225\,T}{(\phi\mu_g c_t)_i}\left(\frac{\sqrt{t_{esr}}}{\tilde{m}_{CPL}h}\right)$
$V_p = \frac{128\,T}{(\mu_g c_t)_i}\left(\frac{\sqrt{t_{esr}}}{\tilde{m}_{CRL}}\right)$	$V_p = \frac{225\,T}{(\mu_g c_t)_i}\left(\frac{\sqrt{t_{esr}}}{\tilde{m}_{CPL}}\right)$
$OGIP = \frac{128\,T\;S_{gi}}{(\mu_g c_t B_g)_i}\left(\frac{\sqrt{t_{esr}}}{\tilde{m}_{CRL}}\right)$	$OGIP = \frac{225\,T\;S_{gi}}{(\mu_g c_t B_g)_i}\left(\frac{\sqrt{t_{esr}}}{\tilde{m}_{CPL}}\right)$
$b = \frac{b_{CRL}k\sqrt{A_c}}{1424\,T}$	$b = \frac{b_{CPL}k\sqrt{A_c}}{1424\,T}$
$y_e = 0.1591\sqrt{\frac{kt_{esr}}{(\phi\mu_g c_t)_i}}$	$y_e = 0.1779\sqrt{\frac{kt_{esr}}{(\phi\mu_g c_t)_i}}$

Other studies include Agarwal [6], Thompson [7], Nabor and Barham [8], Miller [9], and several other papers [10, 11] discussed the long term flow. **Fig 2.2** shows an example of a typically linear flow (half slope).

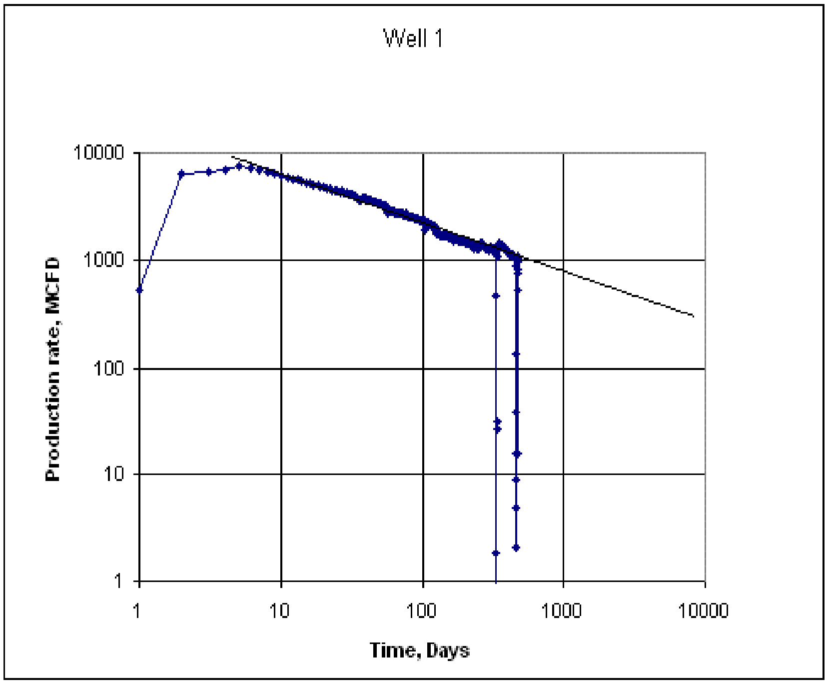


Fig. 2.2 An example of half slope for linear flow on a log log plot

2.3. Previous Work Done Focused on Hydraulic Fracturing

When it comes to low permeability reservoirs its important to understand how the reservoir is going to be fractured what techniques should be used to better fracture the reservoir and better production can be obtained from fractured wells. Different studies are performed few of which are summarized as below:

Wattenbarger and Ramey [12] worked on fractured wells for gas cases. Their study uses numerical simulation to study the pressure transient testing in case of fractured gas wells. In their study it was suggested for gas cases real gas pseudo-pressure should be used.

Agarwal et al.[13] presented numerical solutions for finite conductivity fractures and also discussed how to analyze past performance and predict future performance of low permeability gas wells by massive hydraulic using finite flow capacity type curves.

Al-Hussainy et al.[14] in his study shows a rigorous gas flow equation that was developed by changing the variables in an equation of the form similar to the diffusivity equation. The change in variables can be used as a new pseudo pressure for gas flow that replaces the pressure or its squared used in gas flow. Application of the real gas pseudo-pressure to radial flow systems under transient, steady state or approximate pseudo steady state injection and production is considered.

Recently Mayerhofer and Lolon [15] performed a more advanced study for the complex fracture networks presents the results of integrating micro-seismic fracture mapping with numerical production modeling of fracture networks in the Barnett Shale. An approach is presented, where the fracture network measured with micro seismic mapping is approximated with a numerical production simulator that discretely models the network in both vertical and horizontal wells. This study is an effort to show how production can be improved by fracturing the well in a better way by using micro-seismic monitoring technology (Shown in **Fig. 2.3**) in order to fracture wells. Fracture networks were analyzed and it was observed that larger fracture networks are more productive. Also different stimulations suggestions were made.

In another paper Fisher et al.[16] showed optimized horizontal completion techniques using micro-seismic fracture mapping. Horizontal wells are of great interest now a days in case of shale gas reservoirs and improved stimulation treatments that incorporates multiple stage perforations (Shown in **Fig. 2.3**) and hydraulic fractures is widely in use. Above two papers are of great help to understand these cases. Fisher et al.[16] also explained how the shale gas reservoirs (he studied Barnett shale) have complex fractures which are shown as below in **Fig. 2.4**:

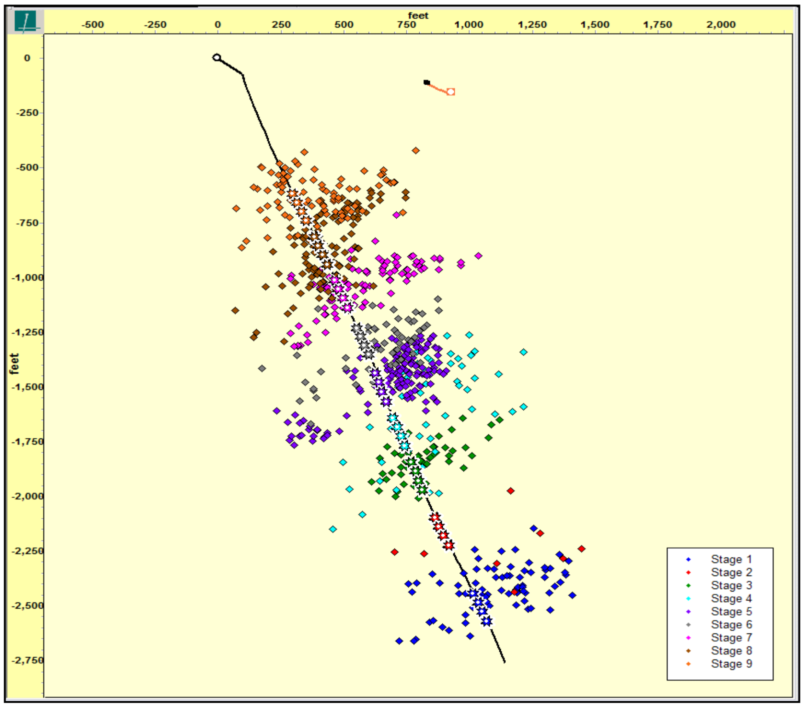


Fig. 2.3 A micro-seismic monitoring of horizontal well fracture networks. Showing different Frac Stages (From SPE 90051[16])

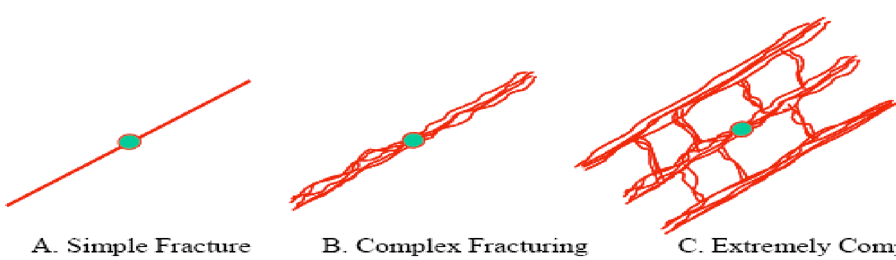


Fig. 2.4 An Example to show the complex fracture networks in shale gas reservoirs (From SPE 90051[16])

2.4. Previous Work Done for Bilinear Flow Analysis

Bilinear flow is also of major interest for production analysis. It is detected in hydraulic fractured wells and also in natural fractures. Also bilinear may be observed in tight gas reservoirs and in Shale gas reservoirs which will be shown later in this study.

Bilinear flow can be caused because of several reasons. Different studies showed occurrence of bilinear flow regime. Cinco-Ley and Samaniego[17] introduced the bilinear concept for the first time and introduced a technique to analyze data on the bilinear flow period for analysis. This study will show many examples that show bilinear flow and a effort will follow this study in order to understand bilinear flow in more detail and to make calculations from such observations. A quarter slope on a Log Log plot as shown in **Fig. 2.5** below shows bilinear flow.

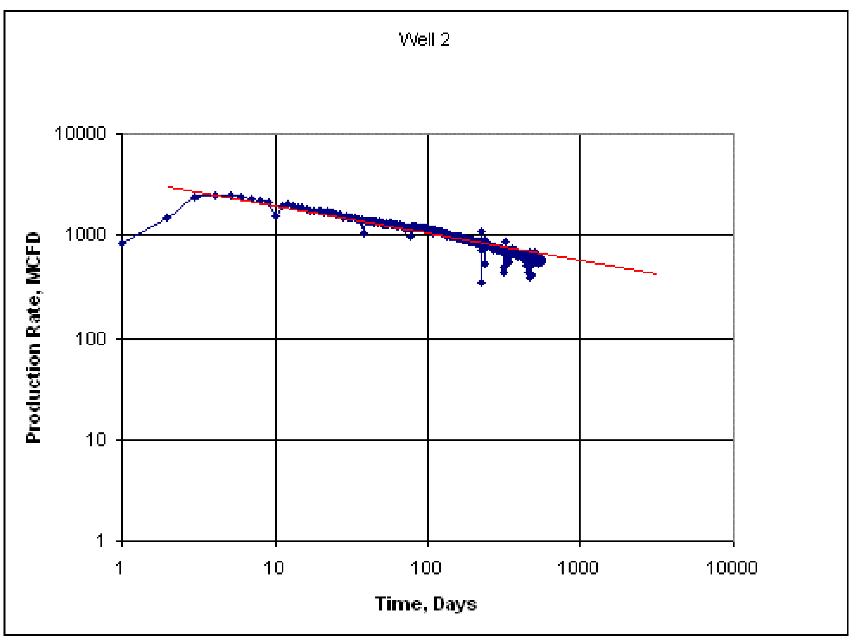


Fig. 2.5 An example of quarter slope indicating bilinear flow on a log log plot

CHAPTER III

DATA MANAGEMENT

3.1. Introduction

In order to do the analysis on the data provided it is important to properly manage the data so that it can be easily understood and used for future studies. This was also part of this research and data is managed according to the usage. This chapter discusses details about the type of data, its division and guidelines about how it is managed.

3.2. Type of Data

Field data is provided by EOG Resources for several Barnett Shale gas wells for production analysis. Data for around 378 wells was provided. Following is the type of data provided:

1. Gas production rates.
2. Casing and tubing pressure.
3. Water production rates.
4. Oil production rates
5. Data for Important field parameter like porosity, bottom hole temperatures, and fluid densities.
6. Data for detailed drilling reports provided in order to investigate perforations intervals, type of fracture fluid, and number of stages for perforations during a fracture job.

Schematics for different wells are also part of the data to observe stages and perforations in the wells with different well lengths shown on it.

3.3. Division of Data

Data is divided in a well-managed format. The whole field data for Barnett shale is divided over different counties. **Fig. 3.1** shows the zone of counties for which the data is analyzed during this study. **Table.3.1** shows the details and statistics of complete data provided divided over different counties mainly between counties in east and west region of Barnett shale in Forth worth area.

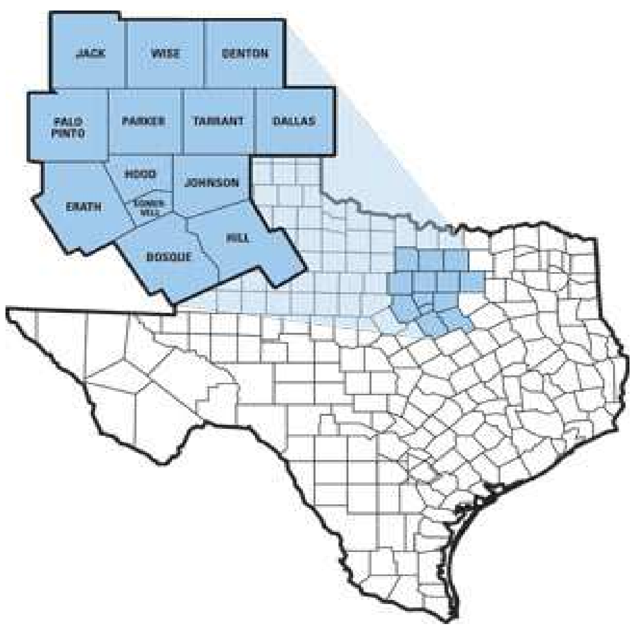


Fig. 3.1 Barnett shale map showing different counties

After initial observations of different wells an effort has been made to divide the data according to different observations i.e. type of flow, usefulness of data and counties.

Table. 3.1 Division of data over different Barnett shale counties

Total Number of Files:	Four	
	Three Excel Sheets	Contains Plots and Well data
	One Summary file	Contains Description of Sheets
East Counties Data		
Counties Names	Johnson, Hill Ellis	
No. of Wells in Each County each year	**County Name-Year**	**Total No of Wells:**
	Johnson-07	38
	Johnson-06	147
	Johnson-05	77
	Johnson-03-04	29
	Hill-Nov-06-April-07	8
	Ellis-May-07-Oct-07	3
		302
West Counties Data		
Counties Names	Jack, Palo-into, Parker, Wise, Erath, Hood	
No. of Wells in Each County each year	**County Name-Year**	**Total No of Wells:**
	Jack, Palo-into, Parker, Wise	48
	Erath, Hood	28
		76
Total No. of Wells	**378**	

The data is plotted for the above wells in the same format. Once the all the wells were plotted a sample of around 130 wells was selected which was of more interest for further analysis. The next chapters will explain that in more detail.

CHAPTER IV

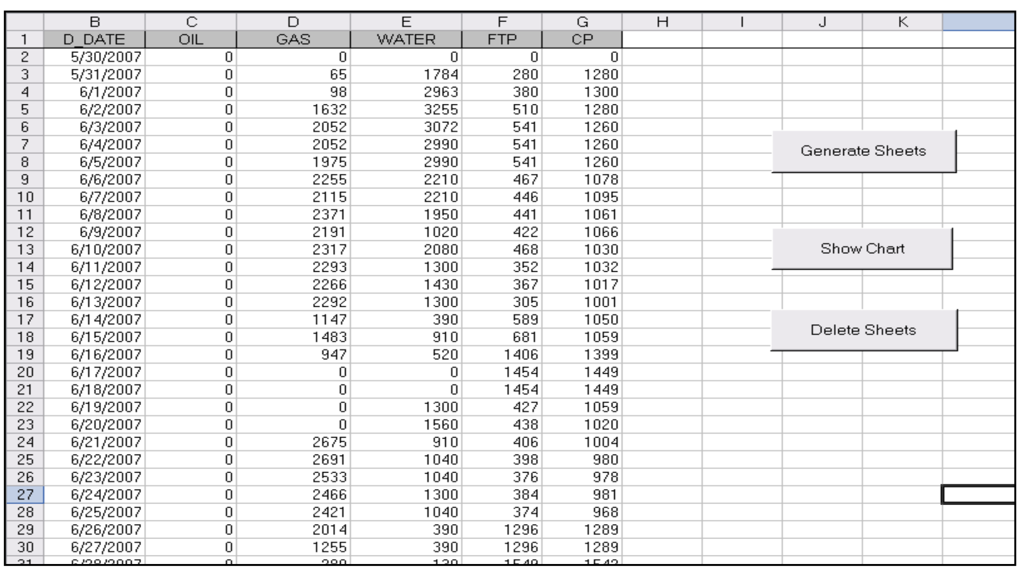
COMPUTER PROGRAM AND USER INTERFACE

4.1. Introduction

In order to handle a large amount of data, a computer program was required to robust different tasks and provides a friendly user interface to analyze and view the data without getting into loads of raw data. This chapter discusses the computer program and guide lines for its use. It is also shown what flow procedure the program follows to make the calculation easy and to perform repetitive tasks with a click of a button.

4.2. Program Interface

A friendly interface was required to perform tasks automatically and to reduce hassle involved while analyzing loads of data. The program is developed using the most popular tool i.e. EXCEL and its VBA interface was used to do the job. **Fig. 4.1** shows the initial format of the program.



	B	C	D	E	F	G	H	I	J	K
1	D_DATE	OIL	GAS	WATER	FTP	CP				
2	5/30/2007	0	0	0	0	0				
3	5/31/2007	0	65	1784	280	1280				
4	6/1/2007	0	98	2963	380	1300				
5	6/2/2007	0	1632	3255	510	1280				
6	6/3/2007	0	2052	3072	541	1260				
7	6/4/2007	0	2052	2990	541	1260				
8	6/5/2007	0	1975	2990	541	1260				
9	6/6/2007	0	2255	2210	467	1078				
10	6/7/2007	0	2115	2210	446	1095				
11	6/8/2007	0	2371	1950	441	1061				
12	6/9/2007	0	2191	1020	422	1066				
13	6/10/2007	0	2317	2080	468	1030				
14	6/11/2007	0	2293	1300	352	1032				
15	6/12/2007	0	2266	1430	367	1017				
16	6/13/2007	0	2292	1300	305	1001				
17	6/14/2007	0	1147	390	589	1050				
18	6/15/2007	0	1483	910	681	1059				
19	6/16/2007	0	947	520	1406	1399				
20	6/17/2007	0	0	0	1454	1449				
21	6/18/2007	0	0	0	1454	1449				
22	6/19/2007	0	0	1300	427	1059				
23	6/20/2007	0	0	1560	438	1020				
24	6/21/2007	0	2675	910	406	1004				
25	6/22/2007	0	2691	1040	398	980				
26	6/23/2007	0	2533	1040	376	978				
27	6/24/2007	0	2466	1300	384	981				
28	6/25/2007	0	2421	1040	374	968				
29	6/26/2007	0	2014	390	1296	1289				
30	6/27/2007	0	1255	390	1296	1289				

Fig. 4.1 Initial program interface

Following are the steps to follow in order to use the program:

1. Import the raw data in the proper format on to the main raw data sheet as shown in the program for several wells but limited to 65k rows due to Excel limitation.
2. Update the well info sheet for different known well parameters.
3. Once done with putting in the required input data click on Generate sheets button. This will generate a separate sheet for every well with individual calculations and seven plots for every well that is required for analysis. Depending upon the amount of data this might take few minutes.
4. Once the sheets are generated properly. Now its time to look at the data. Click on the Show Charts button that pops-up a Friendly user interface to view at individual well. As shown in **Fig. 4.2** below.
5. Select a well by either clicking at the Next Button or by selecting a well from the Selection List located at the left bottom corner. This will connect the user interface with the database. Now select the plots of interests from the top right corner to view at different plots as shown in **Fig. 4.3**.
6. In order to understand the type of flow on Log Log Plot (Top Left plot) flexibility is provided to measure Linear and Bilinear flow. To enhance the proper understanding of a problem, models are created. Click on Show/Hide check boxes for particular case and move the line by clicking on the arrows at the bottom of the plot. **Fig. 4.4** shows the linear and bilinear lines shown after clicking on the check boxes.

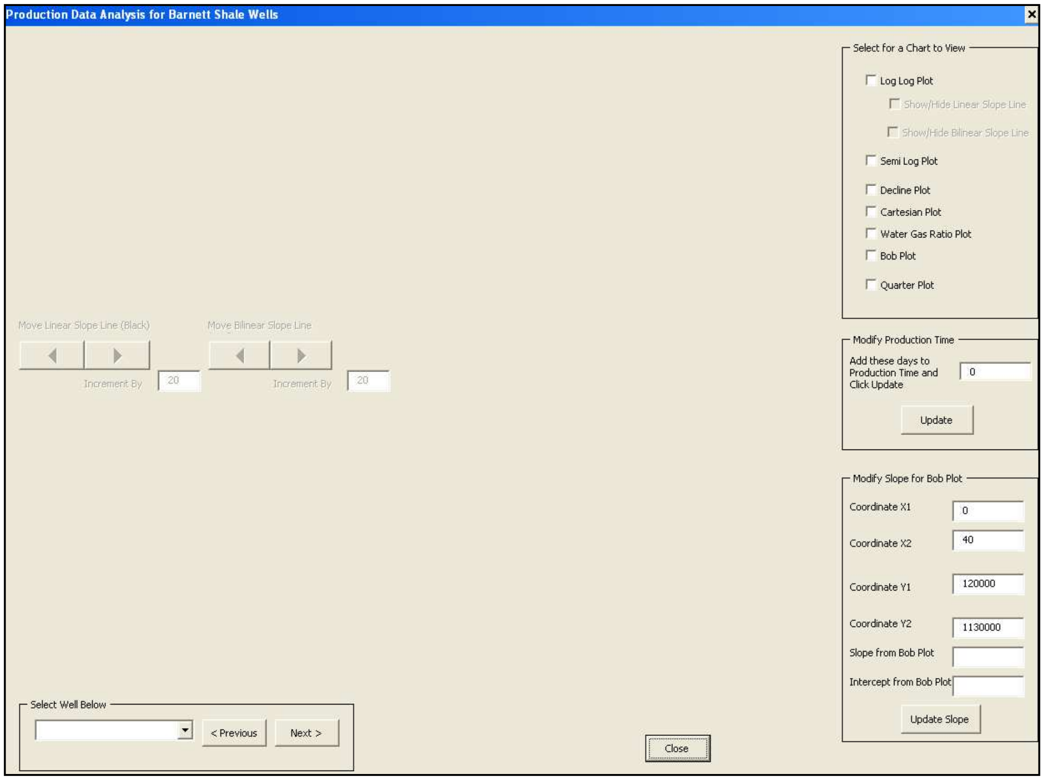


Fig. 4.2 Program User Interface to view individual wells

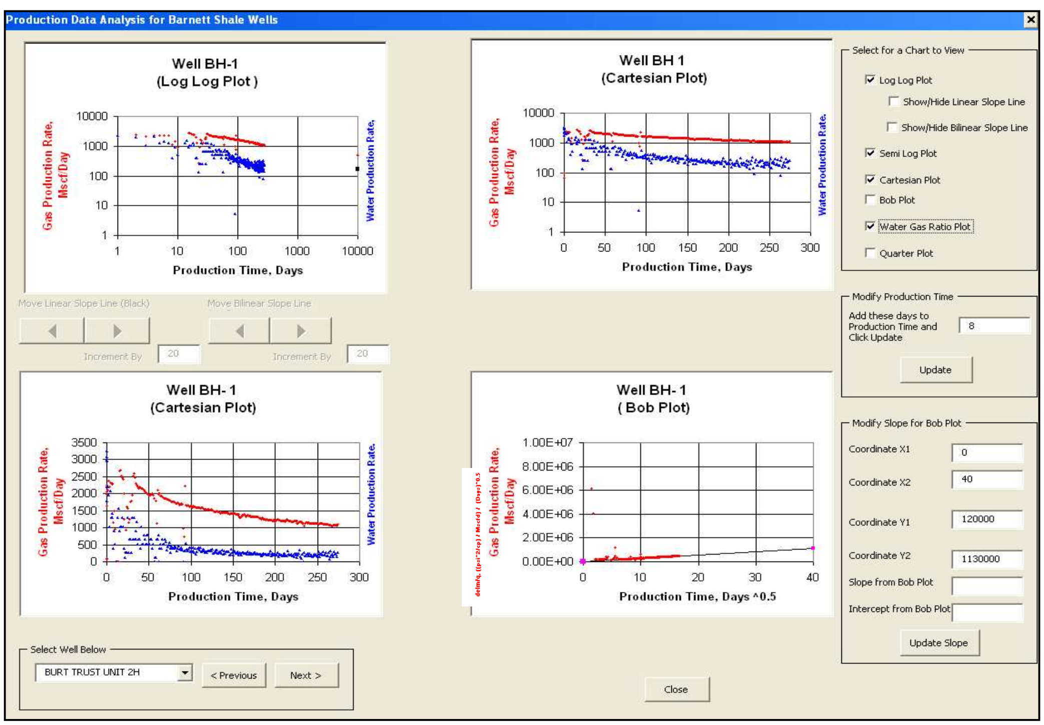


Fig. 4.3 Program User Interface after selecting a well

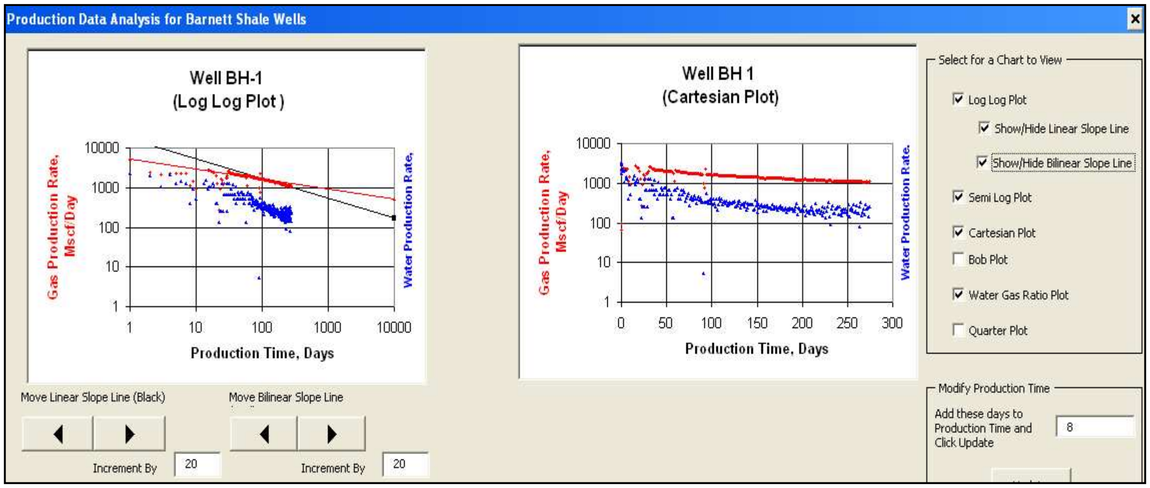


Fig. 4.4 Program user interface after selecting show hide lines for linear and bilinear flow

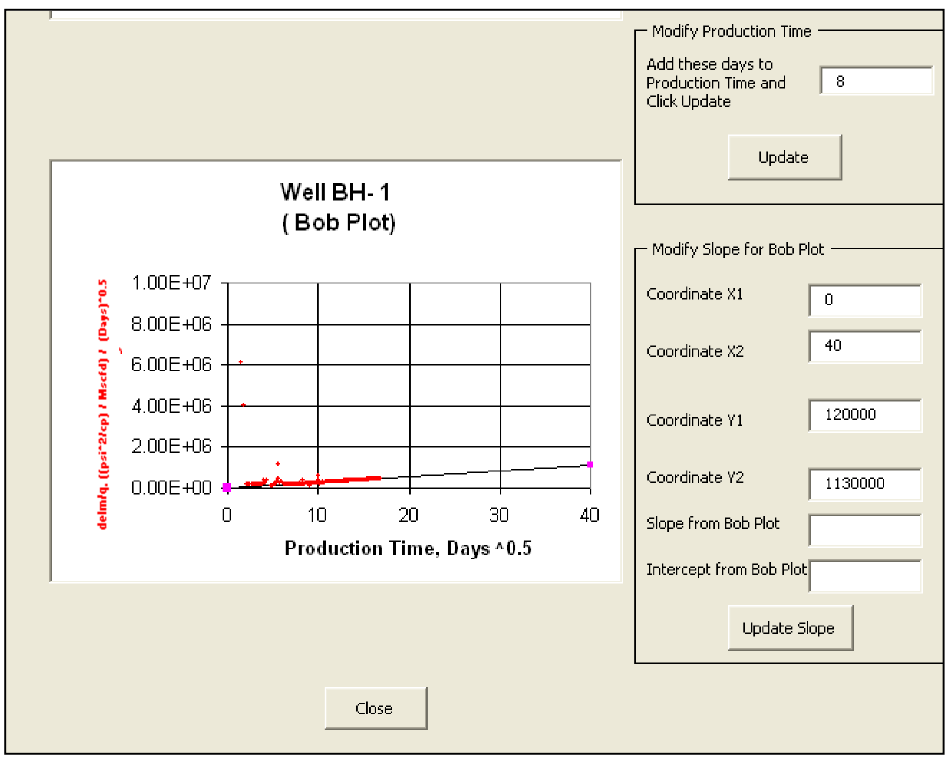


Fig. 4.5 Program user interface showing bob plot and flexibility to calculate its slope

7. Four different charts can be viewed at a time by selecting the corresponding check boxes.

8. **Fig. 4.5** shows Bob plot and input to calculate the slope of Bob plot that is a useful parameter for different calculations. Slope can be calculated by entering values in the available text boxes and clicking on Update button calculates the slope and intercept (if any) for the plot.

9. If required production time can be modified by few days by entering the days added or subtracted in the modify production time area of the interface and clicking on update will update all the plots according to the new time. Original plots can be viewed by adding or subtracting the new time in reverse order.

Fig. 4.6 shows plots and data for individual wells on separate sheets.

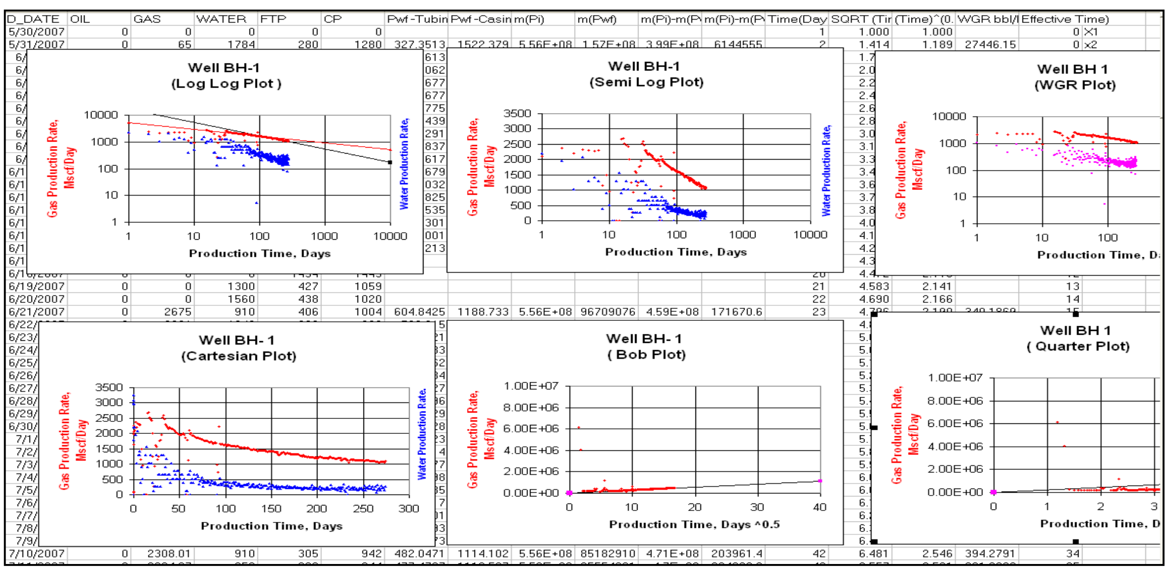


Fig. 4.6 Plot showing generated sheet for Individual well with calculation made and plots generated

4.3. Program Flow Chart

Fig. 4.7 shows the flow chart involved in running the program. Input is taken from different worksheet while the program runs that includes, Sheet names, P Table, Input Calculation, Well Info and Raw data Sheet.

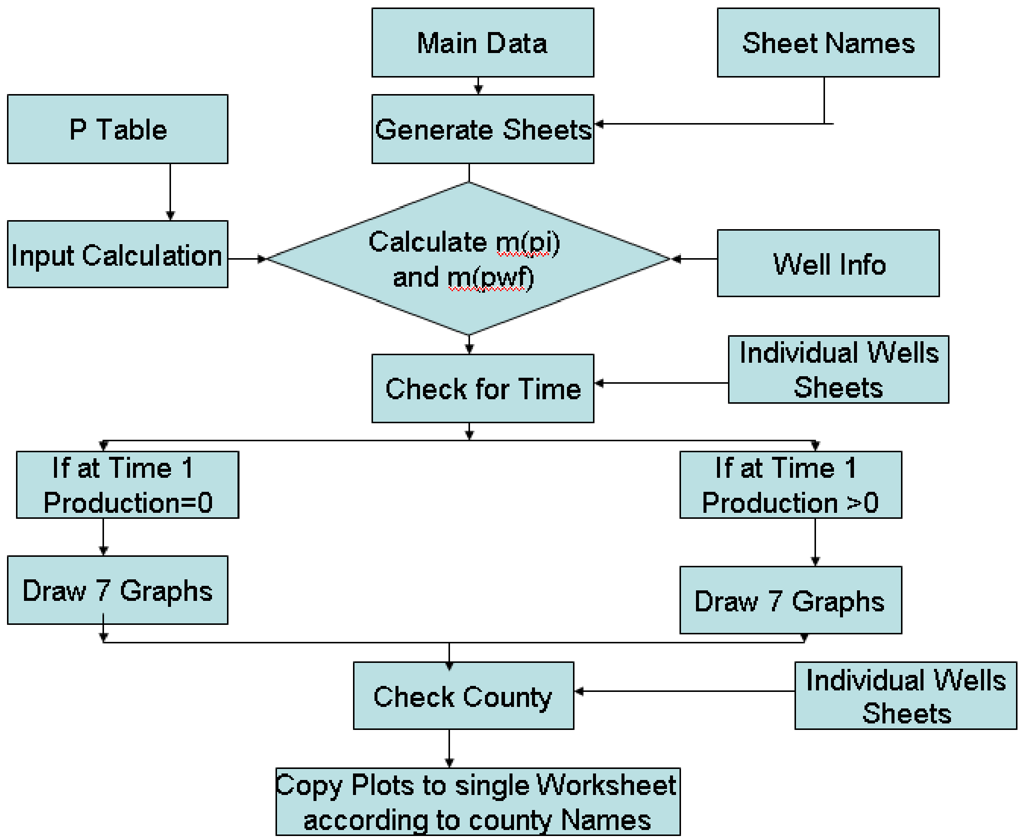


Fig. 4.7 Flow Chart showing the program interface and calculations involved

4.4. Program Calculations

Before generating different calculation some necessary calculation needs to be performed related to gas analysis. Following details the calculation to plot to the right data:

1. Bottom hole pressure needs to be calculated from Tubing and casing pressure. Module is built in the program that does this job. Cullender and Smith [18] method is used to do this.
2. Real gas pseudo pressure m(p) is calculated from the available initial pressure and bottom hole pressure in order to make the Bob plot. A separate module is built to perform this task.

4.5. Type of Plots Generated for Analysis

Fig. 4.8 to Fig. 4.14 show types of plots generated for different wells:

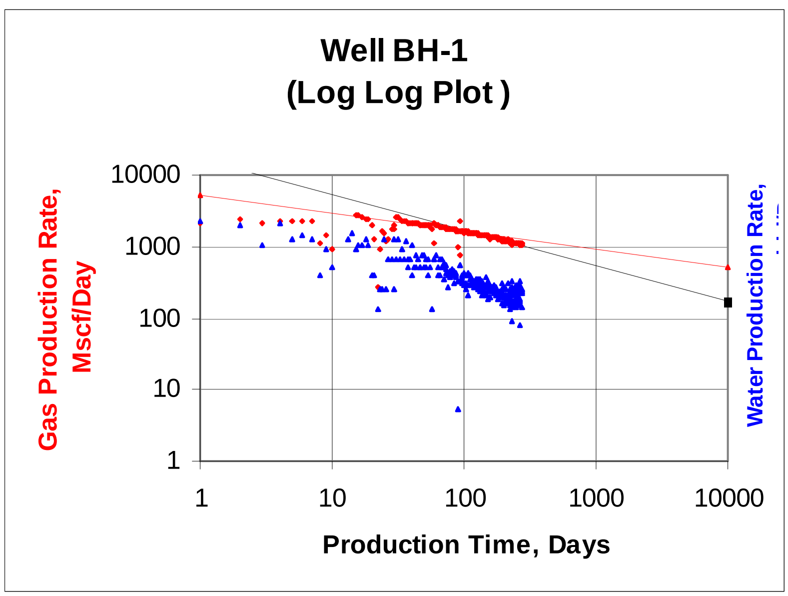


Fig. 4.8 Log Log Plot generated showing gas and water production

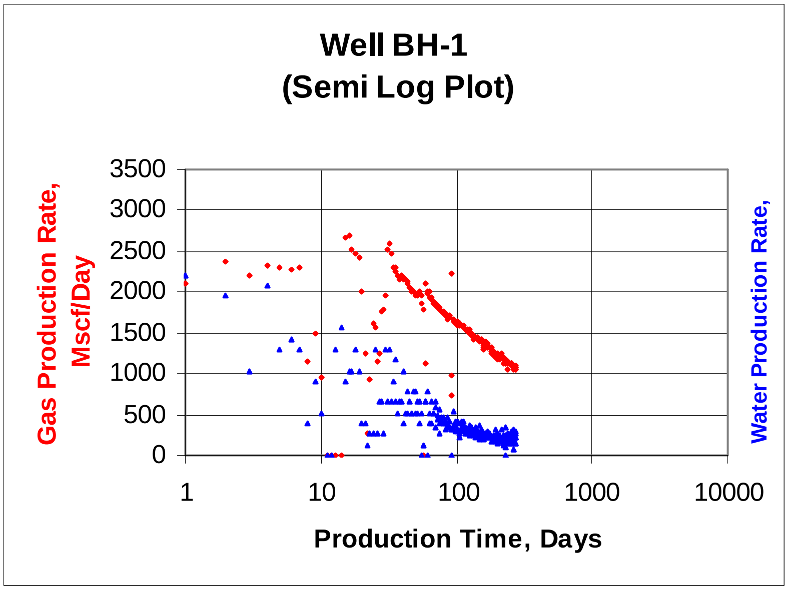


Fig. 4.9 Semi log plot generated showing gas and water production

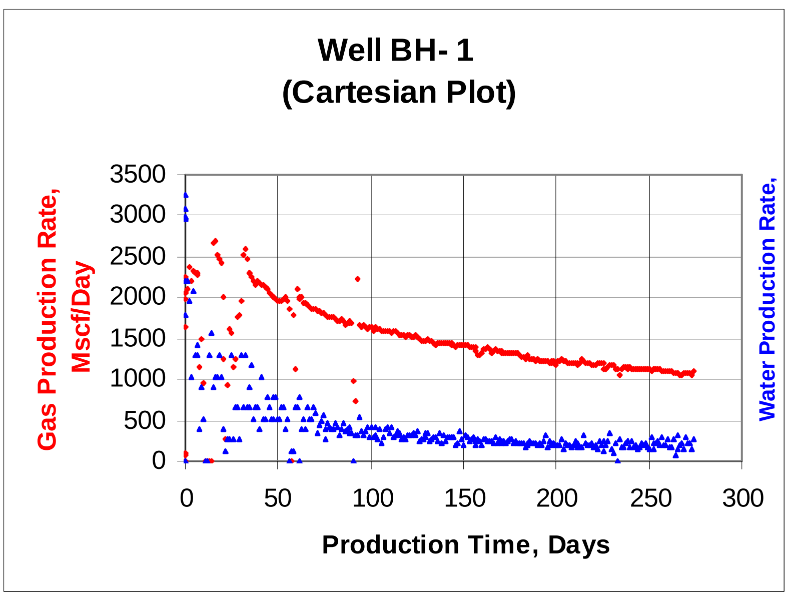


Fig. 4.10 Cartesian plot generated showing gas and water production

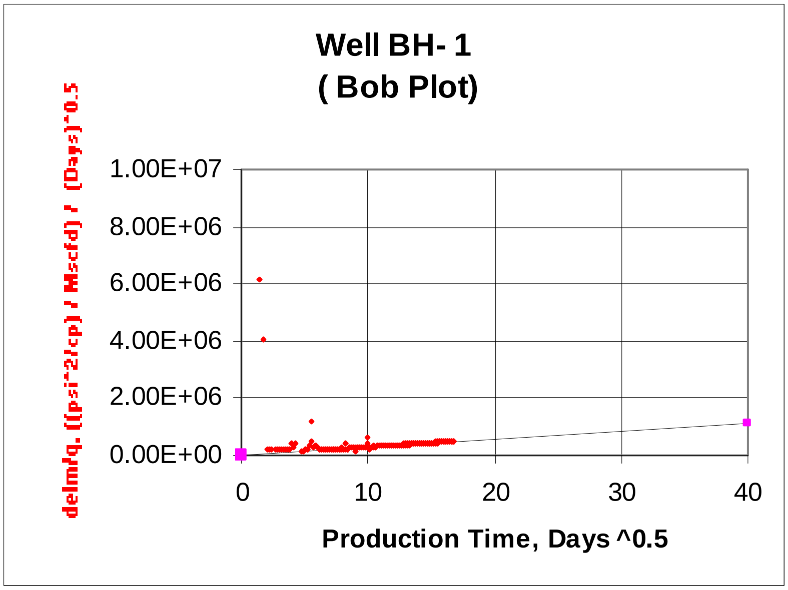


Fig. 4.11 Bob plot generated showing gas production and slope

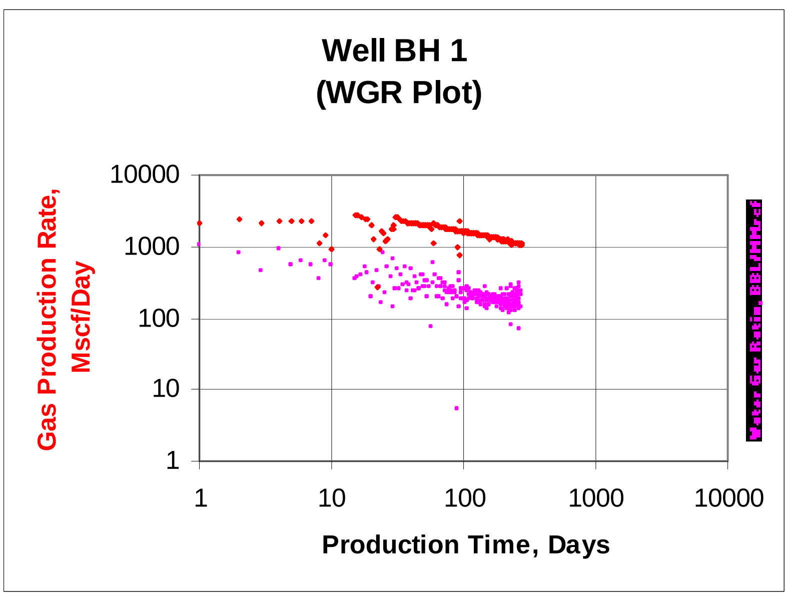


Fig. 4.12 Water Gas Ratio plot generated showing gas production and WGR bbl/MMscf

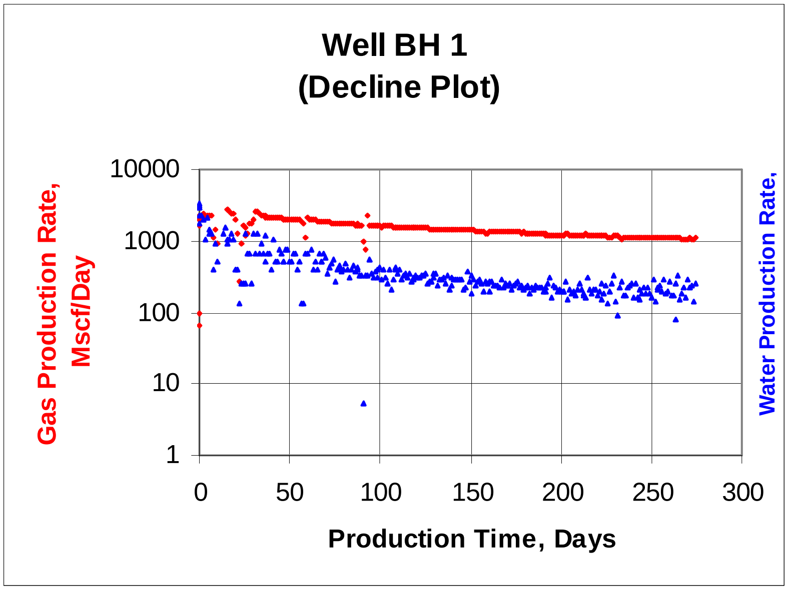


Fig. 4.13 Decline Plot generated showing gas and water production rates

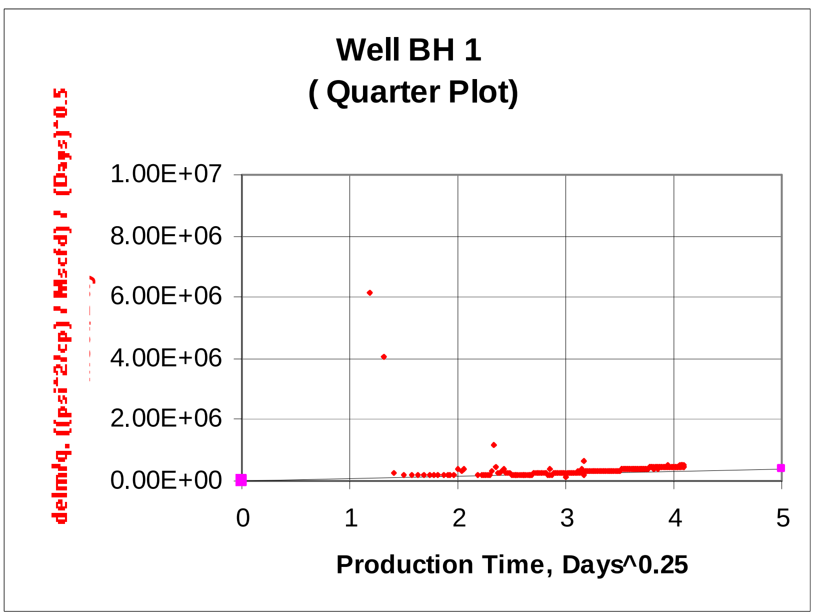


Fig. 4.14 Quarter Plot generated showing gas production and slope in case of bilinear flow

4.6. Suggestions for Improvement

The program can be improved for more tasks to automate the analysis and make it easier for the reservoir engineers to understand a well behavior. Following are few suggestions for improvement:

1. To be able to link program to different databases in order to display several files at the same time.
2. To do the important well parameter calculations like drainage area, permeability etc from with in the program. Right now it is performed separately on a different workbook.
3. Allow the user to select the region of interest from the plots.

CHAPTER V

GRAPHICAL OBSERVATIONS

5.1. Introduction

This chapter shows graphical observations made from the data for the different cases. Linear and Bilinear flows are shown from the original production data for different wells. Cases are shown where mixed flow was observed. Also those wells are shown for which the data is not clear. Water production rates were also plotted along with gas production and water gas production plots observed for any unusual observations. Also different data variations were pointed out. Few of the examples are shown in this chapter while complete list of wells is available in a report by Khan[19] available at Department of Petroleum Engineering, Texas A&M University.

5.2. Linear Flow Observation

Number of wells were observed showing a very clear linear flow for longer period. **Fig. 5.1** and **Fig. 5.2** show few examples of wells that showed linear flow. **Fig. 5.3** and **Fig. 5.4** show linear flow on a log log plot with both water and gas production rates plotted as shown.

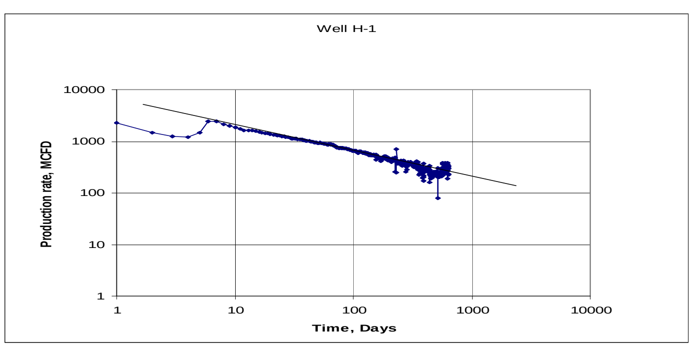


Fig. 5.1 Observed Linear Flow in a well H-1 –Half slope shown by the black line

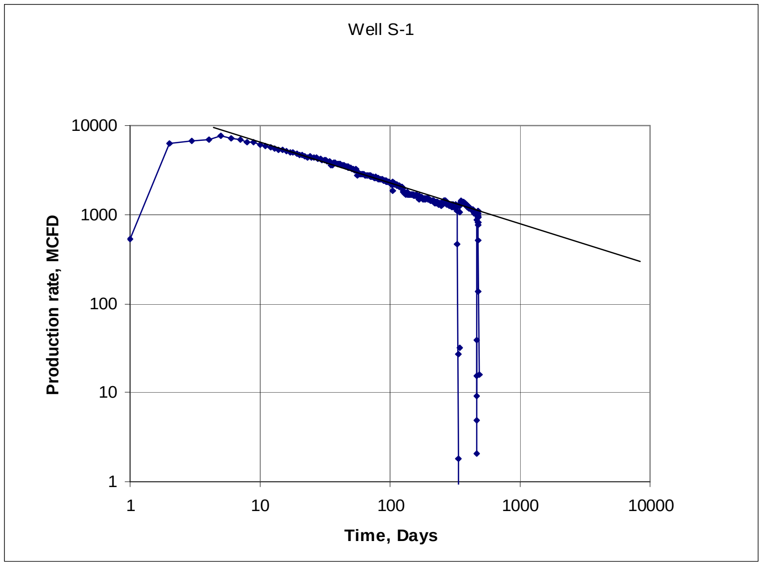


Fig. 5.2 Observed Linear Flow in a well S-1 –Half slope shown by the black line

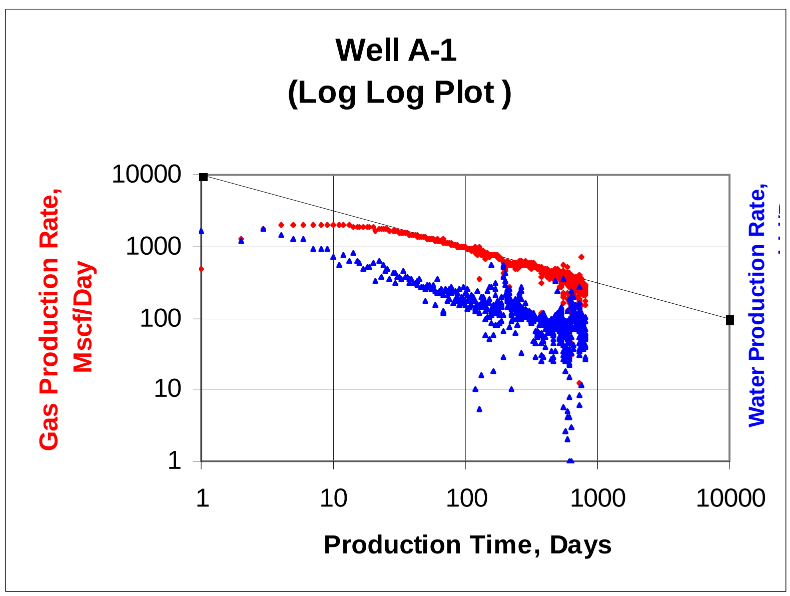


Fig. 5.3 Observed Linear Flow in a well A-1 –Half slope shown by the black line along with water production

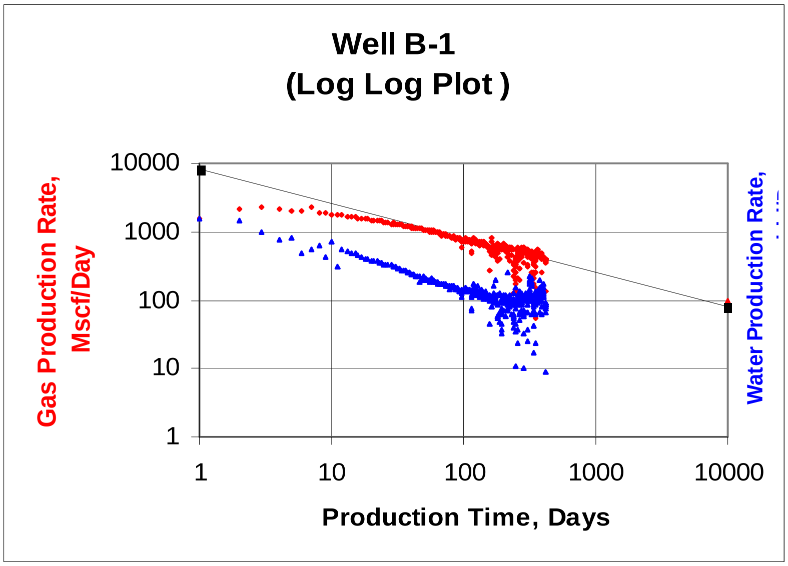


Fig. 5.4 Observed Linear Flow in a well B-1–Half slope shown by the black line along with water production

5.3. Bilinear Flow Observation

Several wells were observed showing bilinear flow regions. **Fig. 5.5** and **Fig. 5.6** show some examples of Bilinear flow cases observed. **Fig. 5.7** and **Fig. 5.8** show bilinear flow on a Log Log plot with both water and gas production rates plotted as shown.

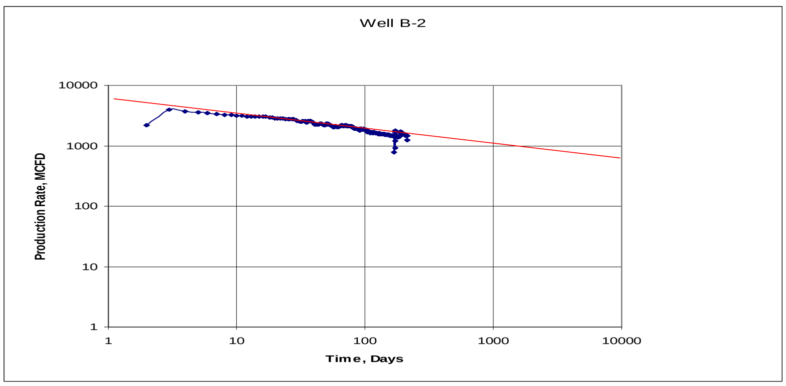


Fig. 5.5 Observed Bilinear Flow in a well B-2–Quarter slope shown by the Red line

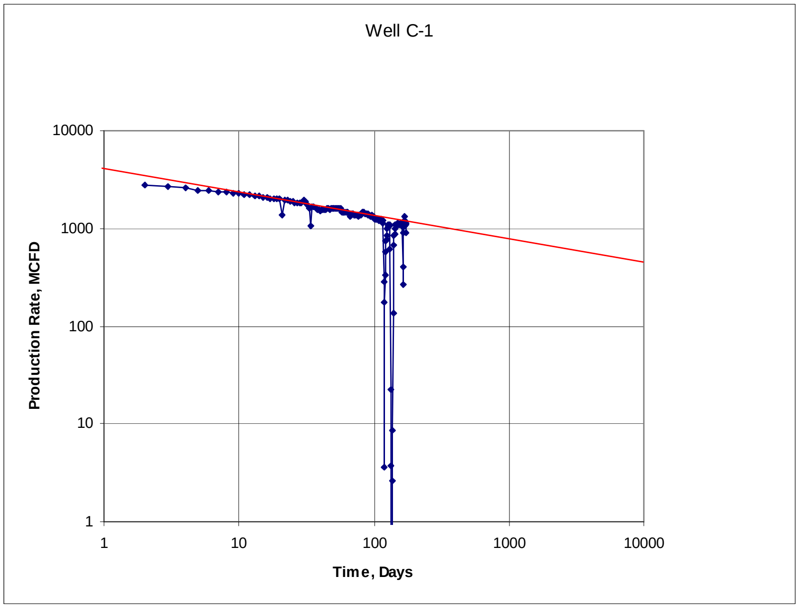


Fig. 5.6 Observed Bilinear Flow in a well C-1 –Quarter slope shown by the Red line

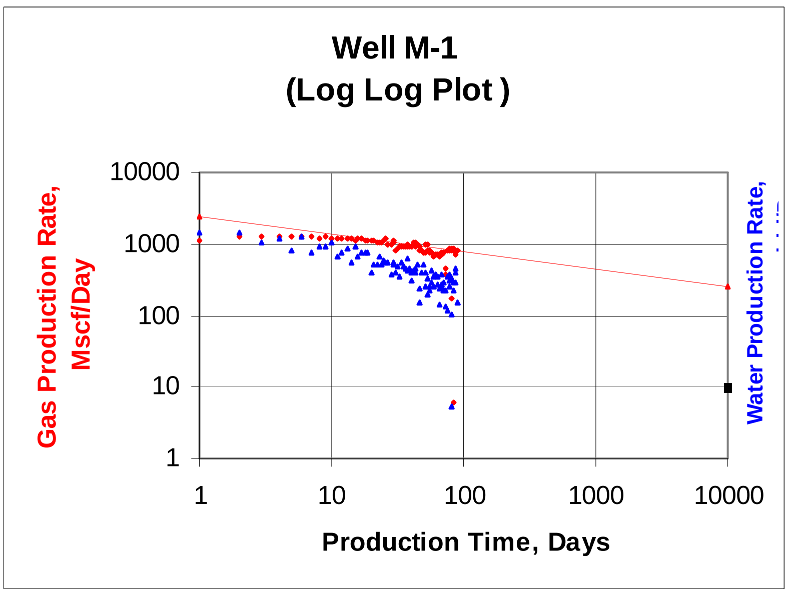


Fig. 5.7 Observed Bilinear Flow in a well M-1– Quarter slope shown by the Red line along with water production

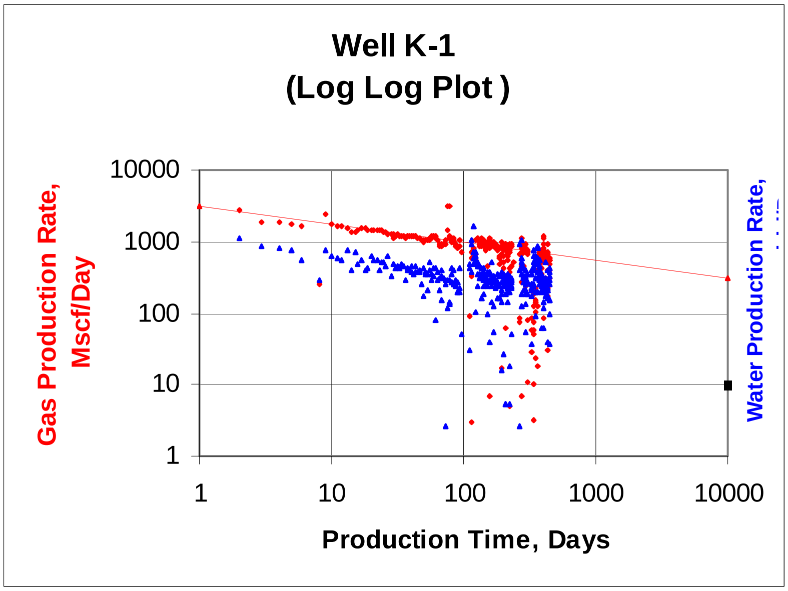


Fig. 5.8 Observed Bilinear Flow in a well K-1– Quarter slope shown by the Red line along with water production

5.4. Mixed Flow Observation

Several wells have both linear and bilinear flow regions. In most of the cases a bilinear flow is followed by a linear flow. Usually the bilinear flow last for first couple of months followed by a long term of linear flow but in some cases linear flow is also for a shorter period. **Fig. 5.9 to Fig. 5.10** show some examples of mixed flow cases observed. **Fig. 5.11 and Fig. 5.12** show mixed flow cases on a Log Log plot with both water and gas production rates plotted as shown.

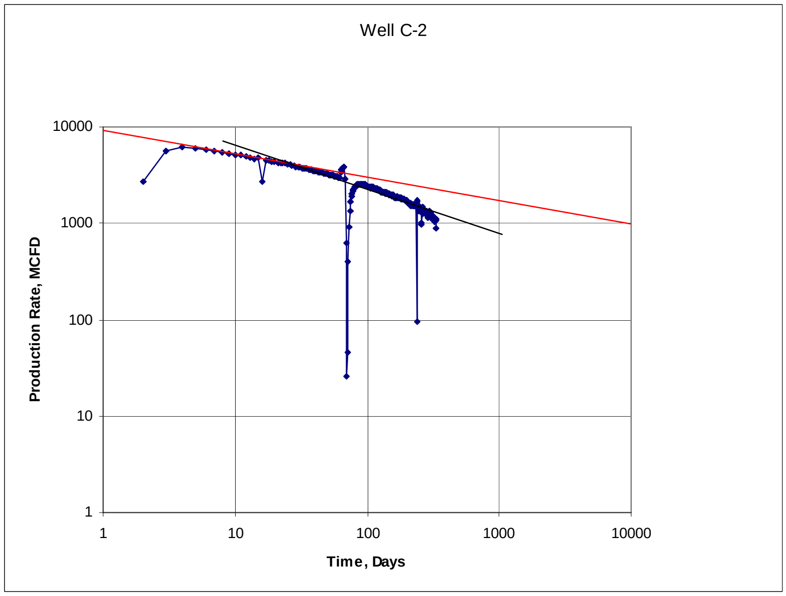


Fig. 5.9 Observed Mixed Flow in a well C-2–Quarter slope shown by the Red line and linear by Black line

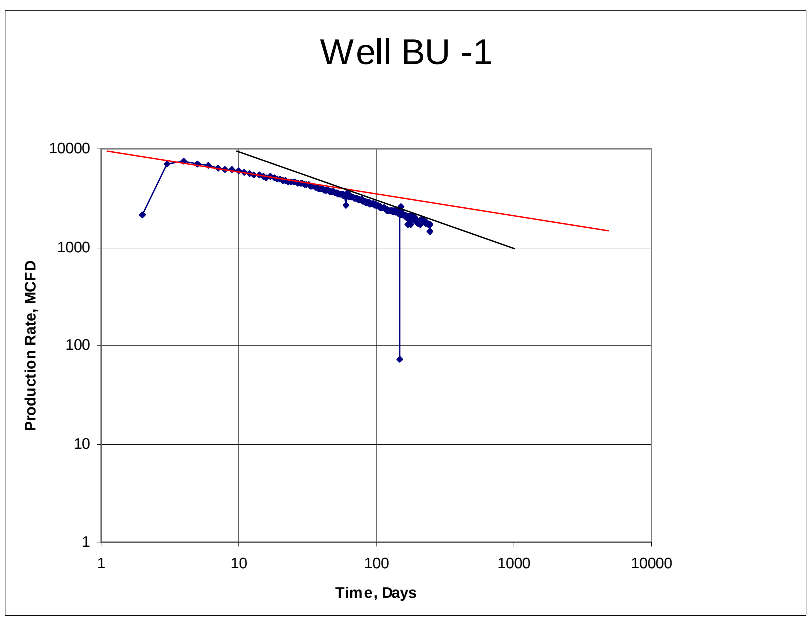


Fig. 5.10 Observed Bilinear Flow in a well BU-1 –Quarter slope shown by Red line and linear by Black line

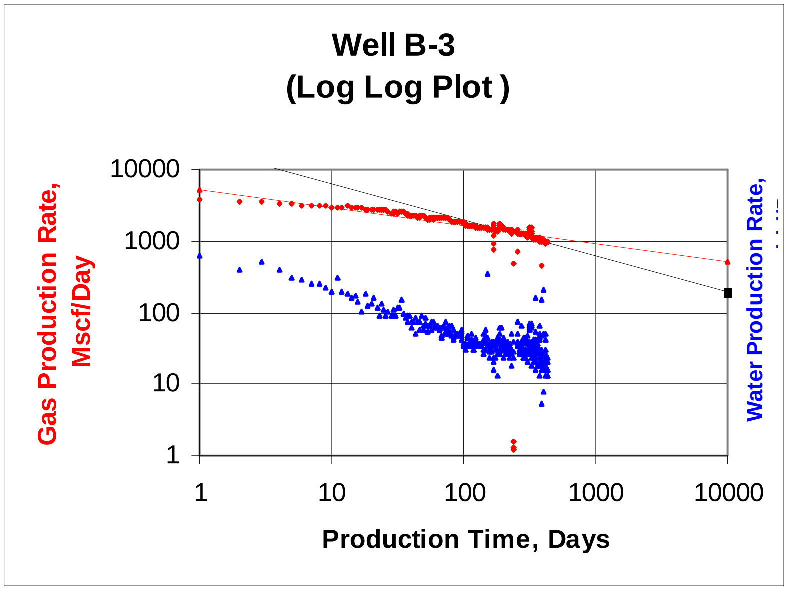


Fig. 5.11 Observed Bilinear Flow in a well B-3– Quarter slope shown by the Red and Linear by Black line along with water production

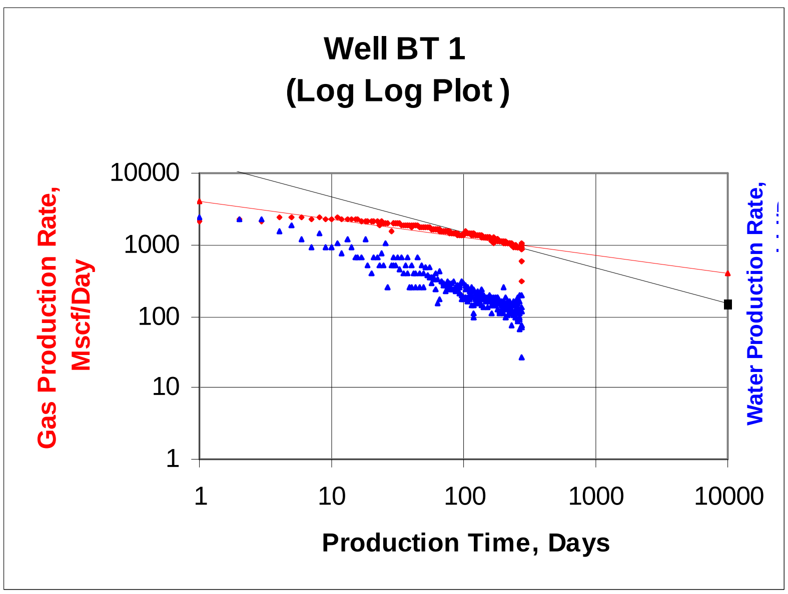


Fig. 5.12 Observed Bilinear Flow in a well BT-1 – Quarter slope shown by the Red and Linear by Black line along with water production

5.5. Unrecognized or Scattered plots

Few wells were observed showing a random and scattered data on plots and doesn't show any proper flow region. **Fig. 5.13 to Fig. 5.16** show some examples of mixed flow cases observed.

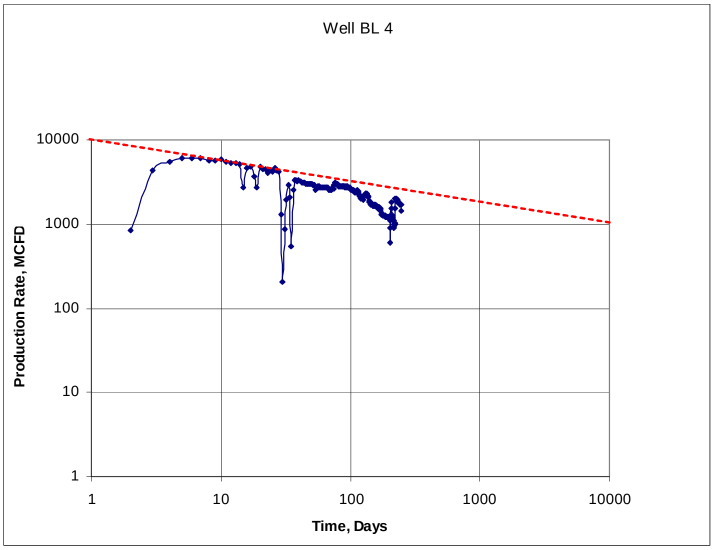


Fig. 5.13 Figure showing a trend that is not exactly quarter slope due to scattered data

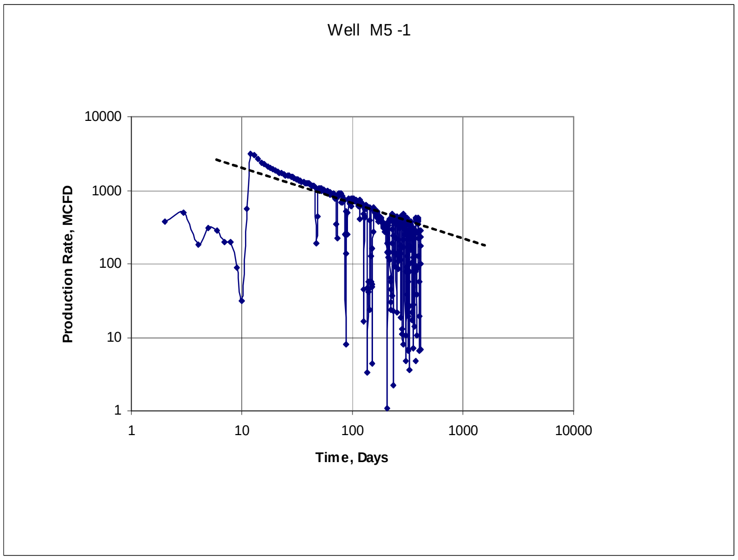


Fig. 5.14 Figure showing a trend that is not exactly half slope due to scattered data

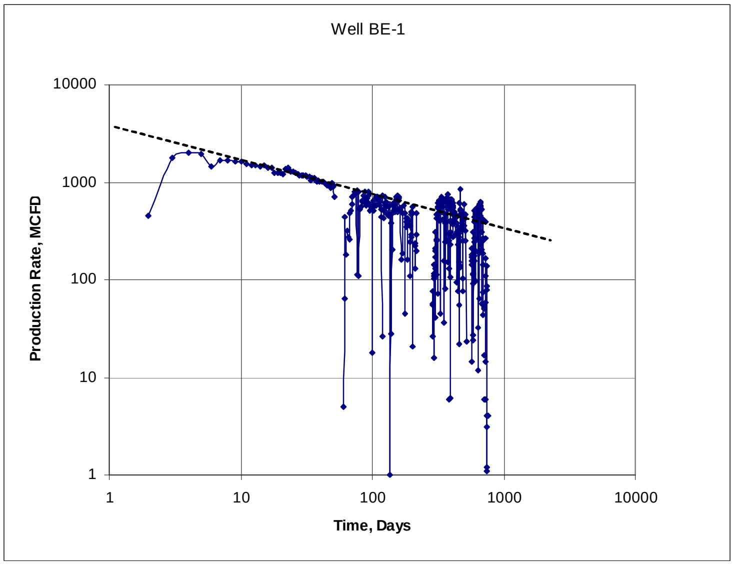


Fig. 5.15 Figure showing a trend that is not exactly half slope due to noise in the data

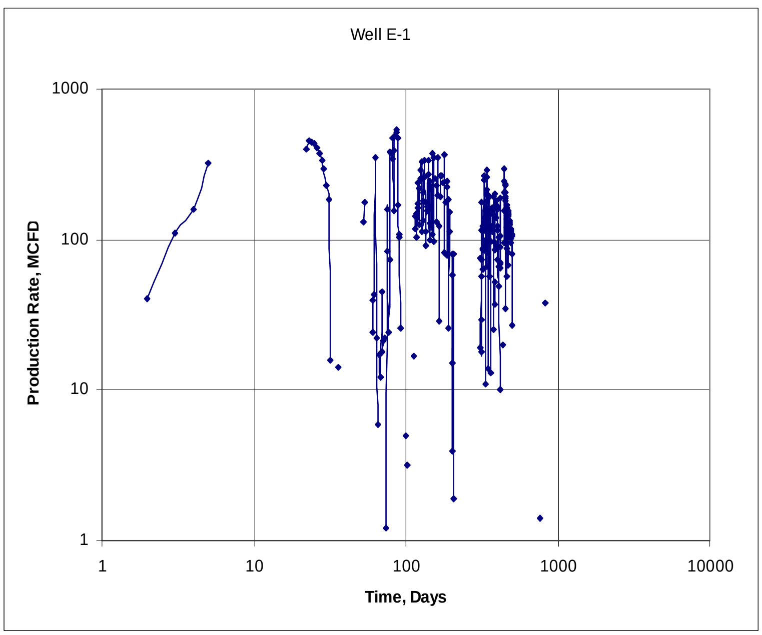


Fig. 5.16 Observed Scattered Plots, production trend not clear.

5.6. Water Production Rate Observations

Water production rates were plotted along with the gas production rates in order to see the behavior of well and to understand how the water production rate changes over the period of time. Water gas ratio, bbl/MMscf plots were also generated to see the water effect more clearly and to understand the well behavior. **Fig. 5.17 to Fig. 5.20** show some of the examples.

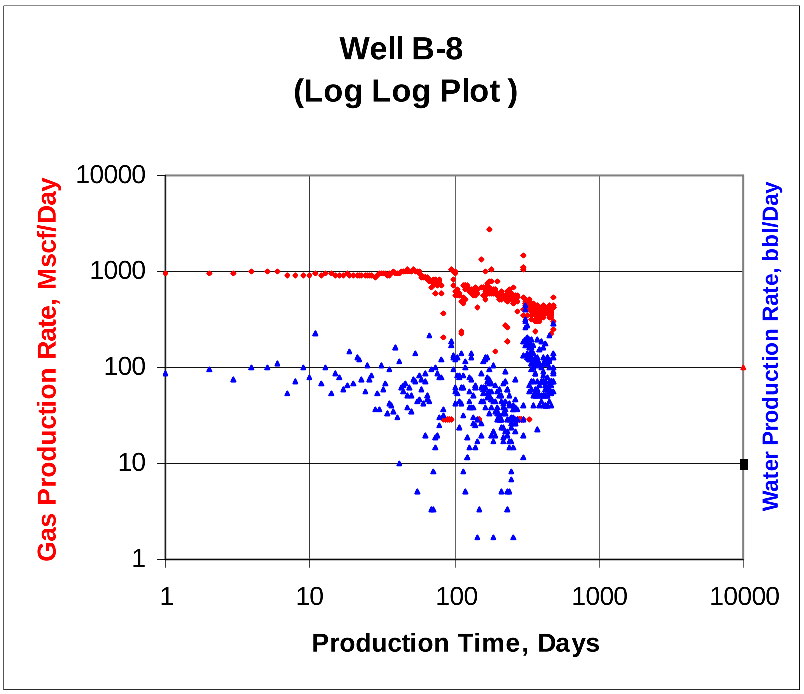


Fig. 5.17 Water Production rate shown on Log Log Plot

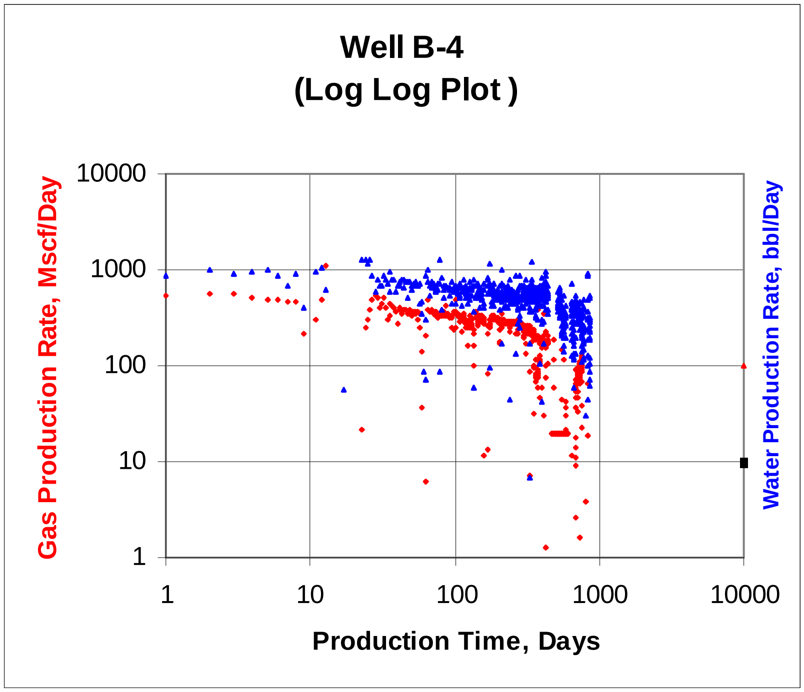


Fig. 5.18 Water Production rate shown on Log Log Plot

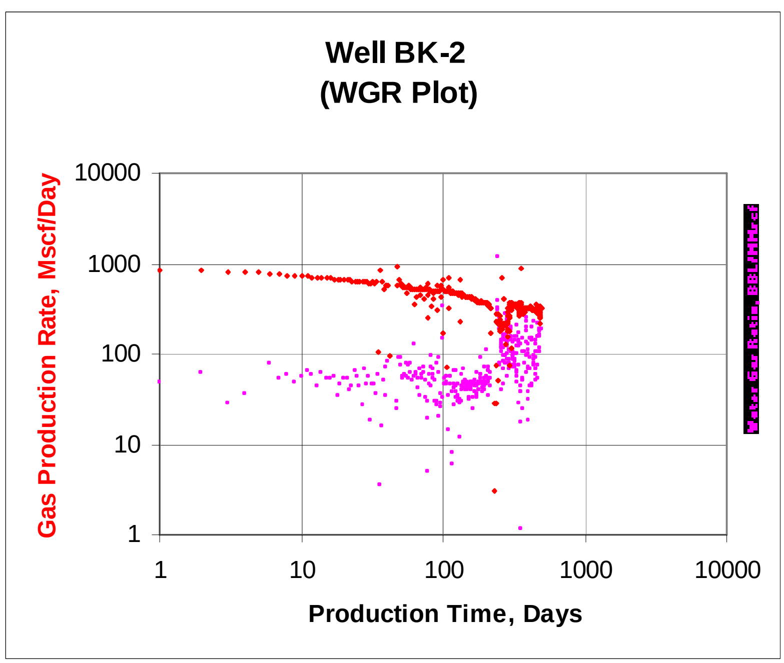


Fig. 5.19 Water Gas Ratio shown on Log Log Plot

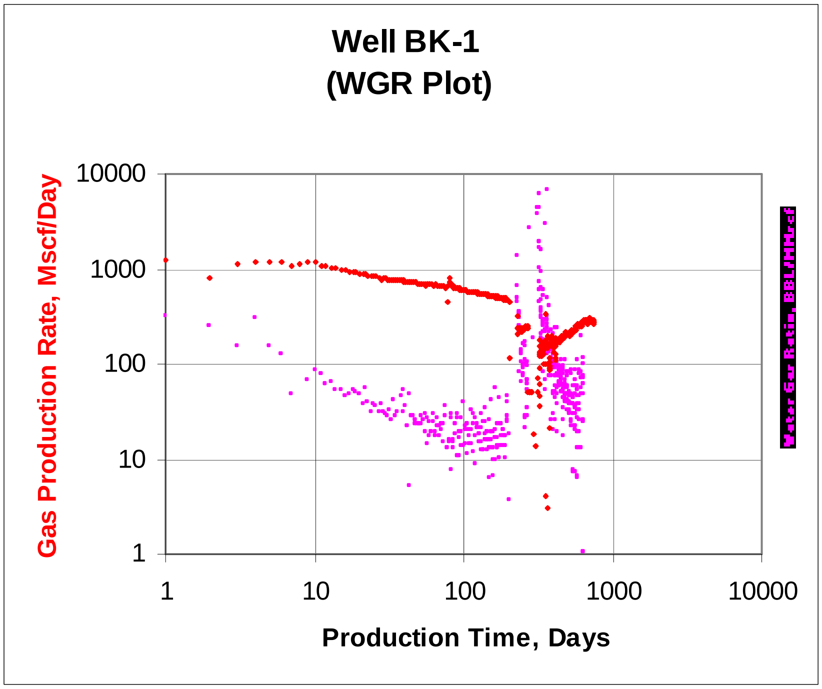


Fig. 5.20 Water Gas Ratio shown on Log Log Plot

5.7. Some Unique Observations

This part of the chapter show some unique observations observed from different plots. **Fig**. **5.21 to Fig. 5.24** show some examples of Gas Production vs. Log of Time plots. A straight line is observed with a slope of one i.e. showing radial flow, even if it shows a different slope on Log Log plot.

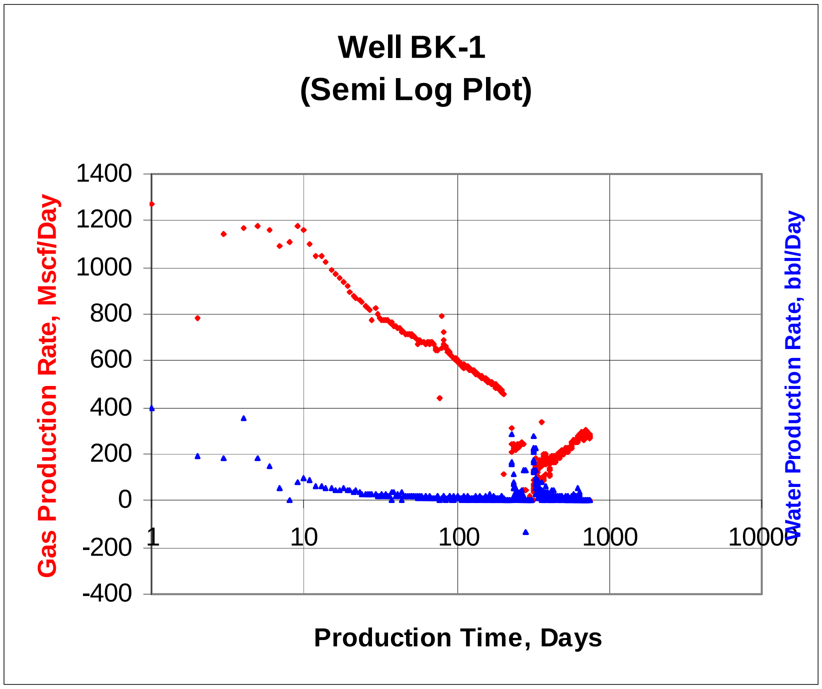


Fig. 5.21 Unit Slope observed on Production rate vs Log of time plot 1

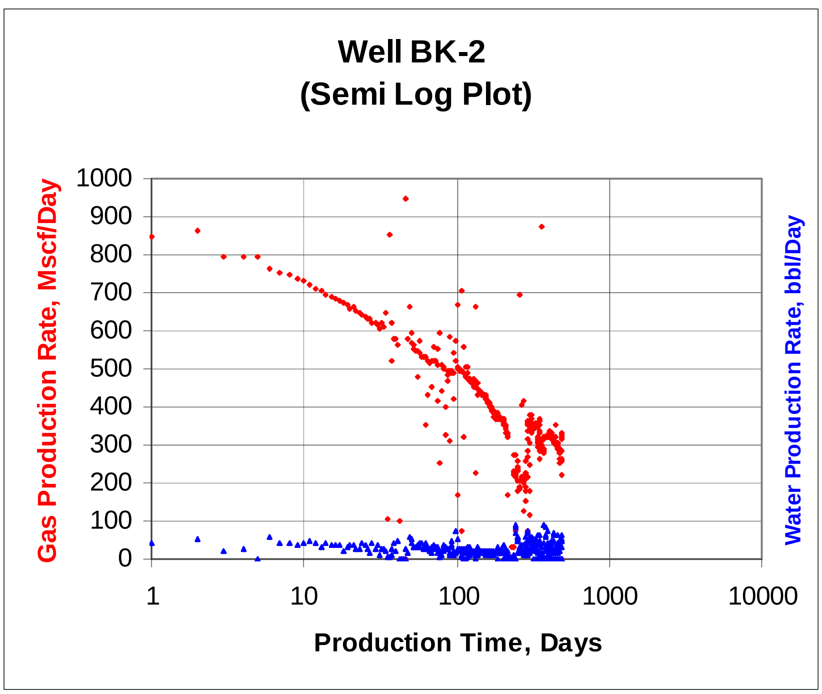


Fig. 5.22 Unit Slope observed on Production rate vs Log of time plot 2

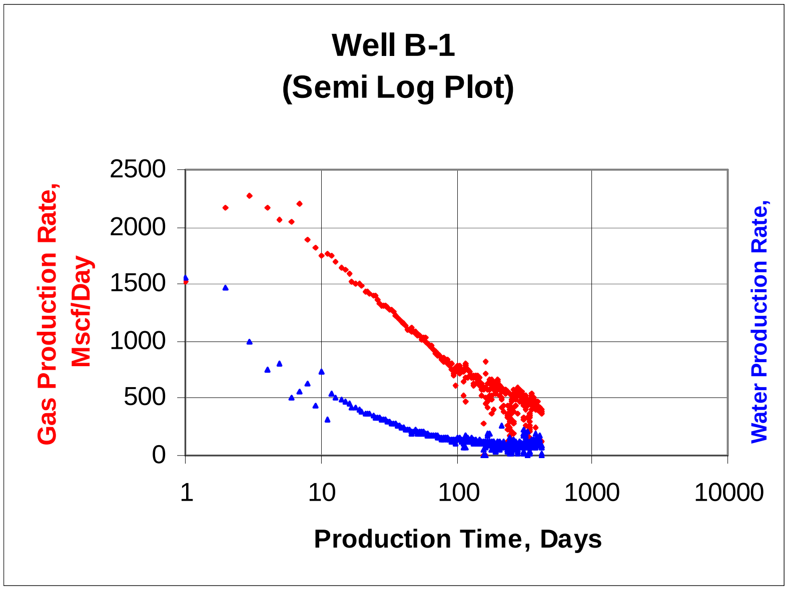


Fig. 5.23 Unit Slope observed on Production rate vs Log of time plot 3

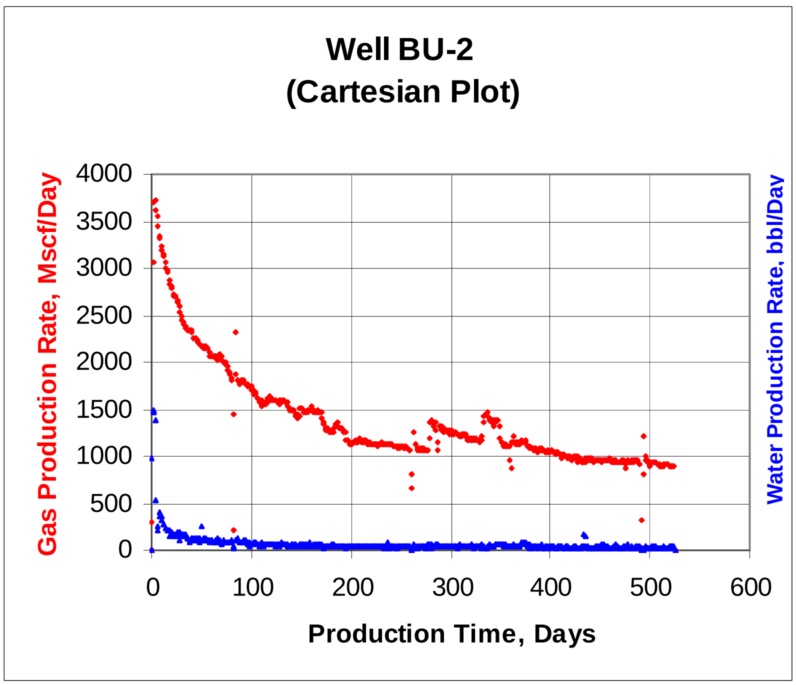


Fig. 5.24 Unit Slope observed on Production rate vs Log of time plot 4

CHAPTER VI

DATA ANALYSIS

6.1. Introduction

In this chapter production data analysis is briefly for linear flow calculations to obtain drainage area by using slopes. Also description of a spread sheet was shown which is to be used in connection with the Program for user interface to do the calculations for individual wells in case of linear flow.

6.2. Linear Flow Calculations

In order to make future predictions and to improve future well performance linear flow region can be used to make certain important calculations. Right now the formulations for linear and bilinear flow to calculate fracture permeability and drainage area for Shale gas are still under study for any modification. The following equation is to be used in order to calculate A_{cm}:

$$\sqrt{k}A_c = \frac{1262\,T}{\sqrt{(\phi\mu_g c_t)_i}}\left(\frac{1}{\tilde{m}_{CPL}}\right) \quad \text{...6.1}$$

An excel sheet is developed to make these calculations for different wells that shows linear flow and thus their slopes can be calculated. These calculations and analysis need further improvement in future work. **Fig. 6.1** shows an example:

			Km =	0.00000015						
				D			(Assuming Same Slope ,m3=m4)			
Well name	m(half-slope)	Begin 1/2 Slope	sqrt(Km) Ac	Acm	h	Xe	sqrt(Kf) Acw	Acw	Kf
	$((psi^2/cp)$ / Mscfd) / $(Days)^{0.5}$	days		sq. ft.	ft	ft		sq. ft.	mD
BU-1	63250		22,531	1,839,622.52	150.00	2,720.00	22,531	816,000.00	0.000762375

Fig. 6.1 Example of excel sheet to make calculations. To be improved in future work.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1.Conclusions

This study presents the production trends of different shale gas wells. It is concluded that different flow regions are identified during the analysis of wells.

Linear flow cases were observed in the majority of wells. Bilinear flow cases were also observed. Some of the cases shown a small trend of bilinear flow followed by long term linear flow and in some cases a very short term linear flow. Bilinear flow followed by short term linear flow might be because of the production for lesser number of days.

When Production rate is plotted versus Log of time a unit slope cases were observed which were not unit slopes on a log log plot. Several of these cases are present in the sample of wells used for analysis.

Actual field data was managed and used to perform the analysis. Different calculations are possible when the slope for different flow region can be measured showing the outer boundary effect on Bob plot.

Using the computer program make it easy and robust to do the analysis and generate different outputs.

Water production was also analyzed besides the gas production to see any important trend or effect on production. Water gas ratio plots can be helpful for this purpose.

7.2. Recommendations for Future Work

In order for more clear understanding of observed wells these wells should be monitored and updated data should also be analyzed in order to see the behavior of wells after years of production.

Computer program should be made more comprehensive and more tools and flexibility should be added to it so that better and robust estimates should be made in future.

Data should be handled in proper format in order to keep track of it.

NOMENCLATURE

A_{cm} = Cross sectional area

A_{cw} = Cross sectional area

B_o = oil formation volume factor, RB/STB

K_f = Fracture permeability

K_m = Matrix permeability, md

m = slope of the log (WOR+C)/C vs. h_{bp} plot

Greek Symbols

ϕ = Porosity, %

ρ = Density, lbm/ft^3

μ = Viscosity, cp

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